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13. ABSTRACT

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Progress in asymptotic wave propagation theory promises to provide sensitive high-resolution techniques capable of determining details of earth structure, in particular velocity gradients in the crust and mantle, and details of the source spectrum. Applications in structural studies have begun to resolve details of the velocity variations within the mantle transition zones and within the mantle-low velocity-zone region.

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Abstract

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Progress in asymptotic wave propagation theory promises to provide sensitive high-resolution techniques capable of determining details of earth structure, in particular velocity gradients in the crust and mantle, and details of the source spectrum. Applications in structural studies have begun to resolve details of the velocity variations within the mantle transition zones and within the mantle-low velocity-zone region.

Source studies have emphasized the importance of source spectrum determinations, radiation pattern characteristics, and the relationship of the spectral character to the physics of the energy production process. Progress in both theoretical and observational work indicates a variety of source characteristics of interest, in particular, for comparable earthquake and explosive events, that earthquake spectra are peaked at lower frequencies indicating a larger characteristic source dimension. The detailed nature of the earthquake spectrum at low frequencies continues to occupy our attention and we expect to resolve differences in theoretical predictions of long-period spectral properties of earthquakes.

I. Introduction

The present report summarizes the work accomplished for the period 1 November 1969 to 31 October 1970. The research accomplished under this grant has been described in detail in the series of technical papers listed in section VIII of this report. Abstracts of these publications and papers presented at scientific meetings during this report period are given in section VII. The research has been divided into the following specific areas for the purposes of this report:

(1) Earth structure studies and inversion theory,

(2) Seismic wave propagation theory,

(3) Seismic source theory and observational studies,

(4) Instrumental developments and automated data acquisition/ processing systems development.

In the following sections (II through V), we briefly summarize the accomplishments and work initiated in these research areas during the past year.

In view of the complexity and wide scope of these investigations, we discuss the overall program in the context of earthquake-explosion discrimination in section VI of this report. The interrelated results of the past year's work in all these research areas are discussed in this reference frame.

II. Earth Structure and Inversion Theory

Research in this area involves two basic activities, namely the determination of seismic velocities, density, and anelastic properties for the earth, and the development of methods of inverting the observations in a systematic manner in order that structural determinations can be obtained from a variety of geophysical data with specified constraints and known resolution.

The work involving earth structure studies is designed to yield velocity models of typical geophysical provinces which can then be used to predict both long- and short-period seismic wave characteristics. In particular, we can predict and interpret both first and later arrival body phases after propagation through one or more particular structural provinces. This will provide a basis for the use of both first and later arriving body phases as aids in the determination of source depth and source spectral character, as well as source radiation patterns. Similarly, earth structure determinations may be used to predict and hence investigate the details of long-period surface waves from a variety of seismic sources. Coupled with the work in wave propagation theory and source theory, detailed structural models will provide the precise

predictions and knowledge of the wave field required to obtain reliable source information, and hence discriminants, in general circumstances. The specific applications to discrimination are discussed in section VI.

Inversion methods are, of course, generally applicable in all branches of science, but in our past work have been tailored to the inversion of seismic data leading to structural models of the earth. However, the theory has been developed with other applications in mind as well, in particular for the inversion of amplitude data related to source properties. Applications in this area are in the planning stages. The use of our well-developed inversion methods and concepts can therefore be extended to provide a systematic approach to the inference of source properties from a variety of observations, and hence multi-varient discrimination.

Our detailed investigations of earth structure and properties have progressed along two general lines. The first involves the use of free oscillation and gross earth data, along with data from high pressure - temperature measurements and body wave travel times, to obtain models appropriate to specific regions or super-provinces, such as oceanic or continental models. The addition of selected body wave and surface wave data to the gross earth data thus gives models which are average earth models appropriate to more specific regions of the earth.

Our second line of attack has been to use "high resolution" techniques to continue the regionalization process even further, so that with super-province models as starting models we obtain a finer resolution of the lateral and radial variations within a region. Thus, for example, a tectonic super-province may be subdivided into structural models appropriate to a mountain province, a plateau province, and a rift province. In addition, variations within these regular provinces have been studied. With the aid of concepts of regionalization based on plate tectonics (especially for the oceans), and using geologic and a wide variety of geophysical observations as a means of regionalizing continents, we have made considerable progress toward detailed descriptions of typical provinces.

In view of this emphasis on lateral variations in earth structure, we have utilized reflection methods extensively as a particularly appropriate, high-resolution, seismic technique. P'dP' phases, that is, reflections of P'P' seismic phases at depth in the mantle and crust, were investigated. P'dP' phases appropriate to the Atlantic-Indian rise, the Ninety-East ridge, and the Indian Ocean regions were studied. Because conversion of P'dP' travel times to depth values strongly depends on the times and relative amplitudes along the multiplicity of P'P' branches, particular attention was paid to the main P'P' phase. Travel times and relative amplitudes for the various branches were determined, and these new data provide a valuable constraint on core models. With such detailed knowledge of the P'P' branches, it has been possible to delineate oceanic structure not otherwise accessible to investigation. For example, in the Ninety-East ridge area the largest amplitude P'dP' phase delineates a zone whose lower bound corresponds to the Moho discontinuity. These arrivals indicate Moho depths of 12 km for the deep ocean and 17 km beneath the ridge and beneath a shoal feature near the ridge. At about 15°S latitude and 6.5° west of the

ridge, a deeper reflecting zone is seen whose lower bound is at 95 km, deepens to 135 km at 3.5° west of the ridge, and then shallows to 70 km under the ridge, both at 15°S and 7°S latitude.

These results are indicative of the power of this method as a means of accurately determining the important lateral variations in the earth's transition zones, as well as a means of determining the depths and velocity gradients in these transition zones. While it does not appear possible to observe details within an oceanic crust with the present accuracy of the data, an experiment designed to observe P'dP' reflections from a continental structure may delineate features within the thicker continental crust. In any case, details of mantle discontinuities can be investigated. For example, the LASA array was used as a beam-forming array to study P'P' and P'630P' phases, the latter being the largest and most consistent of the P'dP' phases. The $dT/d\Delta$ and amplitude data for the various P'P' and P'630P' branches gave positive confirmation of the transition zone at 630 km, and the amplitude spectra comparisons with the P'P' phase indicate that the 630 km transition is a monotonic change in velocity that must take place over a depth range of 5 km or less. This result will enable us to accurately predict amplitudes of direct body phases having turning points in the region of this transition zone, and, of course, provides strong constraints on compositional models of the earth's mantle.

The more conventional refraction profiling for regional structure determinations has been pursued for some time; we have added spectral amplitude observations and wave form observations to the observations of travel times and the apparent (phase) velocities ordinarily used to determine structure. The addition of amplitude data is important not only because it provides more accurate structural determinations, but it results in a systematic sorting out of the complex amplitude effects associated with structure, as opposed to those due to the source. This will, of course, result in greater certainty in the determination of source properties. The use of amplitude data in this way has been made possible largely through the development of asymptotic wave methods. Our theoretical methods are discussed in section III. In particular, theoretical results obtained in our studies of asymptotic wave theory have been applied to published amplitude data measured from predominant travel time branches observed in crustal and upper mantle seismic-refraction studies (Pg, P*, and Pn) in the various geophysical provinces. In general, the amplitudes of all of the branches decay more rapidly with distance than the classical head wave in the western United States and particularly in the Basin and Range province, while they decay less rapidly than classical head wave amplitudes in the eastern United States. This behavior suggests that the major crustal layers and the mantle lid beneath the tectonically active western United States have negative velocity gradients and/or a moderately high anelasticity (Q^{-1}), while the corresponding layers beneath the stable eastern United States have slightly positive velocity gradients.

The determination of velocity structure has been pursued with the objective of characterization of a geophysical province in terms of typical crustal and upper mantle velocities with progressively more detailed determinations of the extent of variations within a province. We have found that geophysical observations (gravity, heat flow, seismic velocities,

etc.) correlate with geological observations in the sense that, within a province, there are well-defined distinguishing properties which change rapidly at boundaries of the province. This implies that from a knowledge of the superficial geology and some geophysical observations, such as gravity, heat flow, or seismicity, it will be possible to infer velocity structure or other characteristics of the region. Seismic body wave studies have been applied in the Basin and Range, the Columbia Plateau, the Colorado Plateau, and in parts of the Canadian Shield. In addition, the surface wave dispersion from explosive and earthquake sources within the Basin and Range province has been measured. Some of these data have been interpreted, and we are in the process of using these data to begin a detailed delineation of the Basin and Range and surrounding provinces. Many of these structure determinations make use of the inversion procedures we have developed.

As another facet of this work, we have employed these inversion methods to determine thermal models for continental provinces in an effort to better define specific geophysical provinces.

Inversion methods have been developed specifically for seismic data of all kinds. However, as already noted, these same inversion methods have been applied to heat flow data as well and, of course, can be applied quite generally. Our greatest effort during the period covered by this report was to develop and utilize the inversion theory for gross earth data.

In particular, a method has been developed for the inversion of an underdetermined system of linear equations under specified constraints and applied to the inverse problem for these data. The technique involves the calculation of a best linear estimate of the solution given the data and the autocorrelation of the noise. Constraints are imposed by specification of the solution autocorrelation operator. A general formulation of this operator in terms of certain inhomogeneous second-order differential equations has been obtained. As applied to the inverse problem for gross earth data, the technique incorporates the location of known discontinuities into the solution autocorrelation to yield a solution which is smoothed between discontinuities. The resolution of the linear system has been examined using the projection operator from the space of models onto the subspace spanned by the data kernels orthogonal with respect to a norm defined by the solution autocorrelation.

Using these techniques, we have endeavored to determine the density and shear velocity in the earth as a function of radius, assuming the compressional velocity is known. Models have been generated which satisfy available normal mode and surface wave data, travel time data of the direct S phase and ScS phase, as well as the mass and moment of inertia. Root-mean-square relative errors for the fits to the data are typically less than 0.3% for this entire data set. Features of these models include non-zero rigidity in the inner core, a low gradient in the density in the lower mantle, and a monotonically increasing density with depth in the upper mantle. Resolving power calculations have indicated the importance of including travel times as a constraint to decouple the perturbations in shear velocity and density.

Abstracts describing the research work accomplished in these studies are given in section VII, part A.

III. Seismic Wave Propagation Theory

Our work in seismic wave propagation theory provides the basis for the interpretations of the observational data leading to determinations of structure and the seismic source itself. It has therefore been closely allied to the more applied problems involving structure and source studies. Thus during the past year, we have emphasized research in one of the more underdeveloped theoretical areas, asymptotic wave theory, since we believe that the largest return in the areas of immediate interest result from applications of this theory. Examples of the usefulness of the theory developed have already been mentioned in the previous section, where estimates of velocity gradients and the earth's anelastic properties have been obtained, in addition to an understanding of the amplitude behavior of both reflected and refracted seismic phases. Applications to observational studies of seismic sources are discussed in the following section.

We have strongly emphasized the development of a practical, higher order ray theory, and hence have developed the asymptotic wave theory in the frequency domain. This work is specifically designed to yield an accurate theory to be used to interpret amplitude spectra data obtained from waves refracted, reflected, or with turning points at and near zones of rapid velocity variations, such as the crust-mantle boundary and the various upper mantle transition zones. It is for such waves that simple ray theory predictions of amplitude behavior fail. Further, ordinary (classical) flat layer refraction theory is too restricted to be very useful, since our work requires a consideration of curvature effects and, more important, accurate representation of the effects of moderate velocity gradients (both negative and positive) on both sides of the transition zones. Thus asymptotic wave-theoretical expressions have been obtained for both SH and P-SV waves from a point source critically or nearly critically refracted from a spherical boundary, below which both the density and velocity may vary as a function of radius. For crustal and upper mantle body waves, the results can be summarized as follows: 1) In the special case of a critical negative velocity gradient ($dv/dz = -v/r$), the critically refracted wave reduces to the classical head wave for flat, homogeneous layers. 2) For gradients more negative than critical, the amplitude of the critically refracted waves decays more rapidly with distance than the classical head wave; for narrow band width data, this decay cannot be easily distinguished from anelasticity (Q^{-1}). 3) For positive, null, and gradients less negative than critical, the amplitude of the "critically" refracted wave decays less rapidly than the classical head wave, and at sufficiently large distances, the direct (or diving) wave dominates the wave form.

This approach to a "better ray theory", which has the simplicity needed for applications, has been applied to the study of the earth's structure, and in future applications will be applied to the interpretation of the spectra from the important caustic phases associated with velocity transition zones in the mantle. These phases can give diagnostic source information at teleseismic distances once we have delineated the detailed nature of the velocity variations near and within these zones. The latter process is close to completion.

A second approach to asymptotic wave theory provides results in the time domain so that comparisons can be made directly with seismograms. This has some intrinsic advantages since the more subtle phase information, as well as amplitude information, is integrated into our interpretations. This approach uses the well-known Cagniard method. We have initiated work on this approach during the later part of the contract period, and our present effort has been directed toward extension and implementation of the theory. One aspect of this work involves wave propagation in the crust at large distances, 400 to 1200 km, which has not been thoroughly studied from this point of view. We are looking into this problem both theoretically and observationally. Observations from both earthquakes and large NTS events, including short- and long-period LRSM recordings, have been gathered and many have been digitized. The theory and resulting programs can treat both P and S sources located anywhere in a stack of layers.

Preliminary studies have shown that for short-period data, the crust acts much like a fluid layer, in that the reflection coefficient at the surface is near (-1) and the large Pg phase has many of the characteristics of the celebrated Airy phase. The energy arriving between Pn and Pg in either arrivals from refractors in the crust-mantle transition zone or multiple reflections trapped between the surface and the Moho, that is, rays that are reflected from the Moho and again at the surface and then refracted along the mantle; such arrivals should have the apparent velocity of the mantle and should have larger amplitudes than Pn. On the other hand, the long-period PL waves behave as if the crust were a solid layer over a halfspace. The reflection coefficient at the surface is no longer (-1), but allows mode changes freely. The reason for the differences in behavior is caused by the low velocity surface layers which have little effect on long wavelengths, but are very important at short wavelengths. Synthetic seismograms illustrating these effects for realistic earth models can be generated, and work is in progress. The structure of the low-velocity zone is being investigated by matching the synthetics to observed seismograms. Figure 1 illustrates this procedure.

Theoretical work in modal representations of the wave field was continued in the direction of surface wave and free oscillation mode excitation from representations of explosive and earthquake sources. In particular, the theory for surface waves in multilayered media generated by point forces has been generalized to include the multipole expansion for finite rupture surfaces and velocities in prestressed media. The surface wave synthesis program is presently being modified to include the more realistic sources. Work has also been initiated on the inclusion of realistic, detailed source representations in existing free oscillation programs.

These modal representations are especially important in the prediction of long-period radiation from seismic sources and will be utilized in the detailed studies of source spectral properties.

Abstracts of papers dealing with wave propagation theory are given in section VII, part B.

IV. Seismic Source Theory and Observational Studies

The principal area of investigation under this grant has been observational and theoretical source studies. These studies are, of course, complemented by our other work, but the focus of our attention has been to provide a fundamental understanding of seismic sources. From the results of this work, we have attempted to extract practical and meaningful criteria for the identification of different kinds of events.

On a theoretical level, we have devised a model for tectonic sources based on concepts of relaxation phenomena in stressed media. Two detailed studies involving applications of this model were undertaken and completed during the present contract period. In both studies, explosive sources were investigated from the point of view of the tectonic effects associated with them. The relaxation source theory was used to predict the anomalous radiation due to tectonic stress relaxation, and comparison to the observations indicated that anomalous radiation from explosions was associated with stress release, most likely from relaxation due to the explosive generated shatter zone. The theory can be used to predict the shatter zone radius and prestress levels. The second of these studies included a detailed analysis of the Fallon earthquake and the Shoal underground explosion, these events having nearly common epicenters and thus common paths of propagation. A comparative study of these two events, therefore, served to delineate differences in the radiation fields from the two kinds of events. We have, for example, found large differences in the spectral ratio of Love to Rayleigh wave excitation, especially at low frequencies, between this pair of events. This spectral relationship is expected theoretically and can be used as a basis of discrimination. Our intent now is to verify the consistency of these differences for a wider magnitude range of events. In addition to relative differences in the radiation fields from explosions compared to earthquakes, some of the absolute properties of the radiation fields from these two kinds of events have been studied. Thus details of the radiation patterns, energy partition, and spectral excitation versus frequency have been investigated. For example, we find evidence for rupture propagation effects for earthquakes in the change of the Love wave radiation pattern shape as a function of frequency and in the spectral minima occurring at critical frequencies.

We have obtained the amplitude spectra from numerous earthquakes and explosions, and while we are at present uncertain as to the long-period level of the spectrum, we have no doubt that the peak or "corner" frequency, corresponding to the frequency of the spectral maximum or flattening of the spectra at lower frequencies, shifts toward lower frequencies with increasing source or rupture dimensions. For explosions, this critical point occurs at a higher frequency than for an earthquake with nearly the same energy or magnitude. For this reason alone, earthquakes excite longer period oscillations than do explosive sources producing the same or similar amount of radiated seismic energy. This effect is therefore the basis of a useful discrimination criteria, and we have investigated its validity for low magnitude events. While only a relatively few events have been studied using the m_b versus m_s criteria, it appears that the relationship holds to low energy events. The effect is predicted theoretically by a relaxation source theory, as well as by a dislocation source

theory. However, the two theoretical models predict different levels for the long-period end of the spectra for an earthquake, and work has been initiated to determine which of these theories is correct in this regard. However, in any event, the shift in the spectra maximum for the two different kinds of sources will result in different long-period excitation for comparable earthquake-explosion pairs.

Very considerable effort has been directed to estimates of source dimensions and stress drops for both earthquakes and explosions. This work is fundamental to our understanding of earthquake mechanics and will also lead to quantitative knowledge of the earth's stress field. Several studies have been carried out and more are in progress. Abstracts describing this work are given in section VII, part C.

Considerable effort has also been directed to extending our theoretical models of both explosive and earthquake sources. Our most recent models are in good agreement with the somewhat limited observations. We intend to expand these theoretical models to more sophisticated geometrical models and to provide predictions of such parameters as theoretical body and surface wave magnitudes for realistic earth structure conditions. This work was initiated during this contract period and is currently still in progress. The abstracts in section VII, part C, describe some of this work, including the observational studies of m_b versus m_s for a wide magnitude range.

V. Instrumental Developments and Automated Data Acquisition/Processing Systems Development

We have continued our development of new instrumentation and have maintained and updated our previous instrumental capabilities. Our emphasis has been in the development and improvement of relatively long-period systems, for both permanent and portable installation. In addition we have attempted to design data recording systems to be compatible with present and future demands of data processing.

Thus we have considered systems designs encompassing the instrumentation itself, the recording system, and the computer-oriented data processing and analysis. In this context, it is useful to view this whole complex as a single entity; we refer to it as an "automated data acquisition and processing system". In conjunction with the demands of other ARPA sponsored research, as well as the work under this grant, we undertook a study to determine what system of this type would be both compatible with our present procedures and serve our future needs by more fully automating our data handling. Figure 2 shows a system which is under development, although already several modifications in details of the system are being studied. However, the general approach illustrated in Figure 2 is being followed. This grant provides partial support for this system.

In view of the importance of long-period information for studies of the seismic source as well as for investigations of structure, we have developed long-period portable units capable of recording seismic data over a broad frequency range. These units, of which there are presently four

under construction, employ 5-second period horizontal and vertical seismometers with very low noise amplifier systems capable of boosting the long-period system response to a level approaching a Press-Ewing response. The 5-second seismometers have the inherent stability required for field work and under appropriate field conditions, the natural periods of these instruments can be lengthened to give higher gain at long periods. These units will be capable of simultaneously recording three components of the motion in the long-period band and also in a short-period band; thereby giving the desired broad band coverage of the seismic spectrum. These units will be used extensively in the near future for relatively near source observations of the seismic radiation field.

At the present time we have completed the preliminary design of the seismometer-amplifier-filter system and are testing and evaluating various configurations of this system for field use. We plan optional recording in either or both analog or digital form, with digital recording preferred for the low sample rate long-period band and analog tape recording for the high frequency band. We have five analog tape recorders (7 channel) on hand and four 60 kc radios and antennas ready for installation in the four completed fiberglass trailer bodies. We have completed work on the seismometers and presently have five vertical and nine horizontal 5-second seismometers. We also have four solar panels on loan from JPL which we will use as the power units for this equipment. Final completion of these units in the form presently envisioned only requires the addition of the digital tape recording units. We hope to obtain sufficient support in the coming year to complete these units with both the digital recording and analog tape recording capability.

Modifications and improvements as well as servicing of existing portable equipment continued throughout the contract period. Minor modifications were also made to upgrade the instrument performance of our long-period seismic installations at Lake Isabella, California, and at Ñaña, Peru. These included the installation of hermetic seals around the strain transducers at Lake Isabella. This was done to preclude the possibility of moisture contamination of the transducers. Improved automatic electrical recentering circuits were installed on the direct (tidal) recorders at both facilities. These latter provide for an increased dynamic range on both strain and mercury pendulum seismometers. A long-period noise correlation test was performed on matched Press-Ewing vertical pendulums. The results of this test are presently being finalized. An additional experiment was done comparing a transducer (vertical pendulum) using a P.A.R. lock-in amplifier technique against one of our "standard" push-pull discriminator transducers. No apparent noise level improvement was observed.

Development of new seismic instrumentation continued; section VII, part D, provides an abstract of a publication describing a new long-period mercury pendulum seismometer.

VI. Implications for Source Discrimination

The relationship of the work carried on during this report period and the remaining problems related to the discrimination of underground explosions and earthquakes can be summarized in terms of the following objectives:

(1) A theoretical basis for discrimination: Theoretical source studies providing the unification of the empirically derived discriminants in present use and providing a basis for the prediction of others over the entire magnitude range of interest. Specific areas of importance are the discriminants based on spectral properties of the source field, the partition of energy in compressional and shear fields, and the nature of the spatial radiation patterns.

(2) Prediction of the near and teleseismic radiation fields: Prediction and isolation of discriminatory seismic phases (including surface waves) based on detailed knowledge of earth structure and an understanding of the nature of the seismic field through the insights and methods provided by advanced wave propagation theory. Specific areas of interest are the isolation and description of phases yielding source depth and spectrum information, including reflected phases, surface waves and large amplitude "caustic phases" associated with mantle transition zones. The resolution of source depth, spatial radiation patterns and spectral properties from effects of the medium, demands a detailed knowledge of the medium itself and the effects of propagation within it.

(3) Observational studies providing discriminant definition plus statistical-empirical support and testing or verification of theoretical predictions: Systematic applications of observational methods to establish discrimination criteria, extending those already defined and providing statistical support for relationships implied theoretically or inferred from preliminary observations. Of importance in such observational work are body wave-surface wave magnitude relationships over an extended magnitude range; spectral ratios of shear to compressional energy especially as exhibited at long periods by Love to Rayleigh surface wave ratios; spectral and energy partition differences, verified and established through quantitative matched filtering methods; verification and statistical support of source field spectral shape differences suggested by theoretical predictions; and radiation pattern relations.

(4) The use, development and deployment of advanced instrumentation: The development of advanced instrumentation for detection and location of events with specialization of instrumentation and data processing techniques towards the fulfillment of the requirements of discrimination for low as well as moderate magnitude events. Some of the important considerations are optimization of arrays of specialized sensors and the development of long-period and broad band seismographs for both permanent installation and portable deployment in field studies of earthquakes and explosions; automation of the instrument-recording-analysis system with applications to detection and discrimination.

VII. ABSTRACTS OF PUBLICATIONS AND REPORTS DURING THIS CONTRACT PERIOD

A. EARTH STRUCTURE AND INVERSION THEORY

Reflection of P'P' Seismic Waves from Discontinuities in the Mantle

Crustal Structure of the Columbia Plateau from the EDZOE Events

Velocity Gradients in the Mantle Lid from Pn Amplitude Data

Partial Melting in the Upper Mantle

Fine Structure of the Upper Mantle

Regional Variations in Upper Mantle Structure Beneath North America

Systematic Inversion of Gross Earth Geophysical Data

Physical Properties of the Mantle

A Generalized Inverse Method for the Inversion of Geophysical Data

Simultaneous Inversion of Mode and Ray Data

Inversion of Gross Earth Geophysical Data Using Well-Posed Stochastic Extensions of Ill-Posed Linear Systems

Systematic Inversion of Continental Heat Flow and Temperature Data

B. SEISMIC WAVE PROPAGATION THEORY

Asymptotic Body Wave Theory for a Spherical Earth with Radial Velocity Gradients

A Contribution to the Theory of High Frequency Elastic Waves, with Applications to the Shadow Boundary of the Earth's Core

Body Wave Reflections from Velocity Gradient Anomalies

C. SEISMIC SOURCE THEORY AND OBSERVATIONAL STUDIES

Observation and Interpretation of Tectonic Strain Release Mechanisms

The Theory of Stress Wave Radiation from Explosion in Prestressed Media

Seismic Radiation from Explosions in Prestressed Media and the Measurement of Tectonic Stress in the Earth

Seismicity of the San Gorgonio Pass

Comparison of P-Wave Spectra of Underground Explosions and Earthquakes

C. SEISMIC SOURCE THEORY AND OBSERVATIONAL STUDIES (continued)

The Kuril Trench - Hokkaido Rise System: Large Shallow Earthquakes and Simple Models of Deformation

A Comparative Study of the Elastic Radiation Fields from Earthquakes and Underground Explosions

Theory of the Seismic Source

A Comparative Study of the Tectonic Effects Associated with Underground Explosions and Earthquakes

D. INSTRUMENTAL DEVELOPMENTS AND AUTOMATED DATA ACQUISITION/PROCESSING SYSTEMS DEVELOPMENT

A Mercury Pendulum Seismometer

A. EARTH STRUCTURE AND INVERSION THEORY

Reflection of P'P' Seismic Waves from Discontinuities in the Mantle, by James H. Whitcomb and Don L. Anderson

A systematic study of the travel times and apparent velocities of precursors of the seismic core phase PKPPKP indicates that these phases are reflections from the mantle. The strongest reflection is from a depth of 630 km. In order of confidence, other reflectors were found at depths of 280, 520, 940, 410 (very weak), and 1250 km (tentative). The weakness of the 410 km reflection was surprising in view of the large velocity increase at this depth indicated by refraction and Love wave studies. This transition region must be broader than the others or involve a smaller density jump. Reflections were observed which were possibly from the top and bottom of the low-velocity zone at depths of 50 and 130 km, respectively.

The above reflections are interpreted in terms of the following solid-solid phase changes, in order of increasing depth: pyroxene-garnet solid solution, olivine → β-spinel, β-spinel → spinel and pyroxene → spinel + stishovite, spinel → post-spinel and garnet → ilmenite or oxides. A spin-spin transition in Fe^{++} may be responsible for one of the deeper discontinuities found by others.

Crustal Structure of the Columbia Plateau from the EDZOE Events, by David P. Hill

In an effort to study crustal and upper mantle structure beneath the Columbia Plateau, the series of EDZOE explosions was recorded along a line extending nearly due south from the shot point at Greenbush Lake, B.C. into central Oregon. Three recording units were used to occupy 49 sites between the Canadian border (Δ = 200 km) and Burns, Oregon (Δ = 790 km).

The first arrivals (Pn) define a travel time branch $T = \Delta/8.05 + 7.54$ sec in northern Washington and central Oregon. Pn arrivals in the Columbia Plateau, however, are early with respect to this branch, attaining a maximum advance of 1.5 sec near Pasco, Washington. A preliminary interpretation of this unreversed Pn data suggests that the crust beneath the Columbia Plateau thins by 10 to 15 km with respect to a reference crust 35 km thick.

Velocity Gradients in the Mantle Lid from Pn Amplitude Data, by David P. Hill

Recently obtained wave-theoretical solutions for the spectral amplitude of "critically refracted" waves for a spherically symmetric, radially heterogeneous earth have been applied to published Pn data for the continental United States and the oceanic crust near Hawaii. The results indicate that the mantle lid beneath the tectonically active western United States has a negative velocity gradient and/or a moderately high anelasticity (Q^{-1}), while the mantle lid beneath the stable eastern United States and the oceanic crust near Hawaii has null or slightly positive velocity gradients.

The inferred negative velocity gradients correlate with regions of subnormal Pn velocities (<8.0 km/sec) and high heat flow (>1.5 HFU); the null and positive gradients correlate with regions of "normal" Pn velocities and heat flow. These results are consistent with laboratory measurements of physical properties of rocks under upper mantle conditions and with anticipated geothermal gradients beneath tectonically active and stable regions.

Partial Melting in the Upper Mantle, by Don L. Anderson and Charles Sammis

The low-velocity zone in tectonic and oceanic regions is too pronounced to be the effect of high temperature gradients alone. Partial melting is consistent with the low velocity, low Q, and abrupt boundaries of this region of the upper mantle and is also consistent with measured heat flow values. The inferred low melting temperatures seem to indicate that the water pressure is sufficiently high to lower the solidus about 200°C to 400°C below laboratory determinations of the melting point of anhydrous silicates.

The mechanical instability of a partially molten layer in the upper mantle is probably an important source of tectonic energy. The top of the low-velocity zone can be considered a self-lubricated surface upon which the top of the mantle and the crust can slide with very little friction. Lateral motion of the crust and upper mantle away from oceanic rises is counterbalanced by the flow of molten material in the low-velocity layer toward the rise where it eventually emerges as new crust. If this lateral flow of molten material is not as efficient as the upward removal of magma, then regions of extrusion, such as oceanic rises, will migrate.

Fine Structure of the Upper Mantle, by C. B. Archambeau, E. A. Flinn, and D. G. Lambert

The spectral amplitudes and travel times of seismic body waves are used to determine mantle velocity structures appropriate to distinct structural provinces within the western continental United States. In addition to basic amplitude and time data, travel-time delays and Pn velocity data from other studies are used as constraints in the systematic inversion of the data for mantle structure. The regional structures for the upper mantle determined in this manner show collectively rather sharp zones of transition (high velocity gradients) near 150, 400, 650 km, and possibly near 1000 km. Comparatively, the regional structures indicate strong lateral variations in the upper mantle structure down to 150 km and possibly as deep as 200 km. The structures appropriate to the Rocky Mountain and Colorado Plateau physiographic provinces show low-velocity zones capped by high-velocity lid zones, with variability in both the lid and the low-velocity zone properties from province to province and within these provinces to a much lesser degree. The mantle properties obtained for the Basin and Range contrast sharply with the Plateau and Mountain structures, with the lid zone being very thin or absent and abnormally low velocities extending from, or very near, the base of a thin crust to 150 km. The velocity determinations are coupled with estimates of the variation of the intrinsic dissipation function (Q) as a function

of depth and frequency. These results show a pronounced low-Q zone corresponding to the average low-velocity zone depth range for the velocity models. The data suggest a frequency-dependent Q, with Q increasing with frequency. In total, the results of the study strongly suggest phase transitions in the mantle including a partially melted region corresponding to the low-velocity zone, the latter being highly variable in its properties over the region studied and strongly correlated with tectonic activity.

Regional Variations in Upper Mantle Structure Beneath North America, by Bruce R. Julian (Ph.D. Thesis)

Several types of seismological data, including surface wave group and phase velocities, travel times from large explosions, and teleseismic travel time anomalies, have indicated that there are significant regional variations in the upper few hundred kilometers of the mantle beneath continental areas. Body wave travel times and amplitudes from large chemical and nuclear explosions are used in this study to delineate the details of these variations beneath North America.

As a preliminary step in this study, theoretical P wave travel times, apparent velocities, and amplitudes have been calculated for a number of proposed upper mantle models, those of Gutenberg, Jeffreys, Lehman, and Lukk and Nersesov. These quantities have been calculated for both P and S waves for model CIT11GB, which is derived from surface wave dispersion data. First arrival times for all the models except that of Lukk and Nersesov are in close agreement, but the travel time curves for later arrivals are both qualitatively and quantitatively very different. For model CIT11GB, there are two large, overlapping regions of triplication of the travel time curve, produced by regions of rapid velocity increase near depths of 400 and 600 km. Throughout the distance range from 10 to 40 degrees, the later arrivals produced by these discontinuities have larger amplitudes than the first arrivals. The amplitudes of body waves, in fact, are extremely sensitive to small variations in the velocity structure, and provide a powerful tool for studying structural details.

Most of eastern North America, including the Canadian Shield, has a Pn velocity of about 8.1 km/sec, with a nearly abrupt increase in compressional velocity by $\sim$0.3 km/sec at a depth varying regionally between 60 and 90 km. Variations in the structure of this part of the mantle are significant even within the Canadian Shield. The low-velocity zone is a minor feature in eastern North America and is subject to pronounced regional variations. It is 30 to 50 km thick, and occurs somewhere in the depth range from 80 to 160 km. The velocity decrease is less than 0.2 km/sec.

Consideration of the absolute amplitudes indicates that the attenuation due to anelasticity is negligible for 2 Hz waves in the upper 200 km along the southeastern and southwestern margins of the Canadian Shield. For compressional waves the average Q for this region is $\gtrsim$ 3000. The amplitudes also indicate that the velocity gradient is at least 2×10^{-3} both above and below the low-velocity zone, implying that the temperature gradient is < 4.8°C/km if the regions are chemically homogeneous.

In western North America, the low-velocity zone is a pronounced feature, extending to the base of the crust and having minimum velocities of 7.7 to 7.8 km/sec. Beneath the Colorado Plateau and southern Rocky Mountain provinces, there is a rapid velocity increase of about 0.3 km/sec, similar to that observed in eastern North America, but near a depth of 100 km.

Complicated travel time curves observed on profiles with stations in both eastern and western North America can be explained in detail by a model taking into account the lateral variations in the structure of the low-velocity zone. These variations involve primarily the velocity within the zone and the depth to the top of the zone; the depth to the bottom is, for both regions, between 140 and 160 km.

The depth to the transition zone near 400 km also varies regionally, by about 30-40 km. These differences imply variations of 250°C in the temperature or 6% in the iron content of the mantle, if the phase transformation of olivine to the spinel structure is assumed responsible. The structural variations at this depth are not correlated with those at shallower depths, and follow no obvious simple pattern.

The computer programs used in this study are described in the Appendices. The program TTINV (Appendix IV) fits spherically symmetric earth models to observed travel time data. The method, described in Appendix III, resembles conventional least-square fitting, using partial derivatives of the travel time with respect to the model parameters to perturb an initial model. The usual ill-conditioned nature of least-squares techniques is avoided by a technique with minimizes both the travel time residuals and the model perturbations.

Spherically symmetric earth models, however, have been found inadequate to explain most of the observed travel times in this study. TVT4, a computer program that performs ray theory calculations for a laterally inhomogeneous earth model, is described in Appendix II. Appendix I gives a derivation of seismic ray theory for an arbitrarily inhomogeneous earth model.

<u>Systematic Inversion of Gross Earth Geophysical Data,</u> by Don L. Anderson and Thomas Jordan

A stable stochastic extension of the pseudo-inverse method has been developed and used to invert, simultaneously, large quantities of gross earth data, including mass, moment, and free oscillations. The errors of the data are treated as noise and serve to stabilize the solution. Many starting, or trial, models and various data sets are used in order to establish the uniqueness of the resulting earth models. A satisfactory model is found for each combination thus eliminating the need for a random search of millions of models. Models are found which differ significantly from the class of models found by Monte Carlo techniques. The composition of the mantle is inferred from shock wave data and velocity-density systematics and can be reconciled with a chrondritic composition if the core is Fe-Ni-S rather than Fe-Ni-Si.

Physical Properties of the Mantle, by Don L. Anderson, Thomas Jordan, and Bruce R. Julian

Stable solutions, in a stochastic sense, can be found for ill-posed or underdetermined linear problems by a method due to Franklin. The method is applied to the inversion of free oscillation and body wave data to obtain best linear estimates of the seismic velocities and density in the earth for various noise and solution autocorrelation functions. The resolving power as a function of depth is determined for each set of data. Important features of the resulting models are negative shear velocity gradients between the discontinuities and a low-density zone in the upper mantle. Lattice theory provides an explanation for the negative shear velocity gradient in the spinel portion of the mantle and the positive but low gradient in the post-spinel part of the mantle. The theory makes it possible to utilize all the seismic data in discussions of mantle mineralogy. Previously only the density and Φ were amenable to theoretical interpretation.

A Generalized Inverse Method for the Inversion of Geophysical Data, by Thomas Jordan and C. B. Archambeau

A new method introduced by J. N. Franklin can be applied to solve the ill-posed systems of linear equations characteristic of geophysical inverse problems. This method, originally described in terms of statistical processes, is summarized in terms of linear operator theory. Useful aspects of the approach include the opportunity of allowing for the effects of the approximation of a spherical, radially inhomogeneous earth model rather than an "exact" earth model (e.g., laterally inhomogeneous) in the generation of an inversion matrix, and the opportunity to systematically generate models satisfying particular constraints. The resolution of combined body and surface wave seismic data for the western United States is examined as a first application. Implications of the resulting crust-upper mantle models are discussed.

Simultaneous Inversion of Mode and Ray Data, by Don L. Anderson, Thomas Jordan, and Martin L. Smith

Elementary and reasonable physical considerations are used to place constraints on earth models which are calculated by the inversion of large quantities of gross earth data. These considerations include information which is not contained in the data set to be inverted and contribute substantially to the problems of uniqueness and resolving power. We assume, for example, 1) good correlation between density and seismic velocities; e.g., the shear velocity and the density may change rapidly in regions where the compressional velocity changes rapidly; 2) an autocorrelation for a given model parameter based on physical considerations, such as finite strain theory; 3) various starting models based on high resolution techniques such as body wave travel time, velocity, and amplitude studies; 4) density must increase with depth below some 100 km, and 5) ρ_o, λ_o, and μ_o, as determined by finite strain theory, must be greater than zero.

These very weak constraints lead to unique models for the earth's interior which retain the features built into the starting models by high resolution techniques, including upper mantle reflection data.

Inversion of Gross Earth Geophysical Data Using Well-Posed Stochastic Extensions of Ill-Posed Linear Systems, by Thomas Jordan

An inverse, introduced by J. N. Franklin, based on a well-posed stochastic extension of an ill-posed linear system is applied to the inversion of geophysical data. New information is introduced with the specification of solution and noise autocorrelation operators and can be used to restrict the solution manifold. The solution obtained, which is unique, is shown to be "the best linear estimate" for a given norm. The extreme stability of this method makes possible the simultaneous inversion of large quantities of gross earth geophysical data, including mass, moment, eigenfrequencies of free oscillation, travel times along seismic rays, and group velocities of surface waves. Density and velocity models of the earth are obtained. The questions of the resolving power of the data and the effect of the starting model are examined. For solution autocorrelations compatible with mineralogical considerations in the mantle and core, the effects of variations of the starting model are shown to be small.

Systematic Inversion of Continental Heat Flow and Temperature Data, by J. Bernard Minster and C. B. Archambeau

A simple thermal model of the crust and upper mantle under the North American continent is obtained by systematically inverting heat flow and temperature data in the steady-state linear approximation. The stable method proposed by Jordan and Franklin is used to modify a starting model, under specified constraints. We successively present our assumptions, the construction of a starting model, and its inversion; the assumptions are discussed a posteriori. The results are compared with existing models and with information obtained from different geophysical approaches.

B. SEISMIC WAVE PROPAGATION THEORY

Asymptotic Body Wave Theory for a Spherical Earth with Radial Velocity Gradients, by David P. Hill

Asymptotic wave-theoretical expressions have been obtained for waves from a point source critically or nearly critically refracted from a spherical boundary, below which both the velocity and density may vary as functions of radius. The effect of boundary curvature is found to map into an effective positive velocity gradient in the corresponding flat problem. For crustal and upper mantle body waves, the results can be summarized as follows: 1) In the special case of a critical negative velocity gradient (a gradient equal and opposite to the effective curvature gradient), the critically refracted wave reduces to the classical head wave for flat, homogeneous layers. 2) For gradients more negative than critical, the amplitude of the critically refracted wave decays more rapidly with distance than the classical head wave. 3) For positive, null, and gradients less negative than critical, the amplitude of the critically refracted wave decays less rapidly than the classical head wave, and at sufficiently large distances, the direct "diving" wave dominates the wave form. Preliminary indications from the application of these results to published Pn amplitude data suggest that the mantle lid has a negative velocity gradient in the western United States, and a null or slightly positive gradient in the eastern United States.

A Contribution to the Theory of High Frequency Elastic Waves, with Applications to the Shadow Boundary of the Earth's Core, by Paul G. Richards (Ph.D. Thesis)

The diffraction of P and S waves by various obstacles is studied theoretically, in order to evaluate frequency dependent corrections to ray theory for elastic waves which travel nearly along the earth's core shadow boundary.

Most of the properties of this scattering process are conveniently illustrated by a simple earth model, which gives rise to a problem in plane strain. This model is an infinite homogeneous elastic solid in which a steady-state plane body wave (of the type P, SV, or SH) is incident on a ciruclar cylindrical cavity. A Poisson summation is used for the scattered elastic potentials, and contributions from waves diffracted at least once around the cylinder are neglected. Simple approximation formulae are developed to examine the behavior of P, SV, and SH waves on and near their geometrical shadow boundary behind the fluid. Computed numerical results are believed to be valid for frequencies above 0.03 Hz.

The solution method, which may be regarded as a corrected Fresnel theory, is taken through four successive stages of generalization to study increasingly realistic earth models: (i) diffraction of cylindrical waves from a line source. For this problem our solution is in excellent agreement with the results of an ultrasonic model experiment conducted by Teng and Wu (1968). (ii) Diffraction by a fluid cylinder of cylindrical waves from a line source. (iii) Diffraction by

a spherical fluid of spherical waves from a point source. Here we find good agreement between numerical results from our approximate method, and computation of the exact Poisson line integral.

The final stage of generalization, to study (iv) diffraction by a spherical fluid/solid discontinuity in a realistic radially heterogeneous earth, is obtained by methods similar to (iii), but after an extensive revision of Hook's (1961) discussion of elastic potentials in general media. In our approach, we recognize that the designation of P and S displacements is somewhat arbitrary in heterogeneous elastic media, but becomes precise in the high frequency limit of ray theory (in which P and two S components are decoupled). These facts are used for radially heterogeneous isotropic earth models to establish three potentials (P, S, T) with the properties (a) that $T(\underset{\sim}{r}, t)$ is decoupled from P and S, and is a potential for SH motion, (b) the coupling of P and SV waves is reflected in a system of coupled scalar equations for $P(\underset{\sim}{r}, t)$ and $S(\underset{\sim}{r}, t)$, and (c) in the high frequency limit we have $P(\underset{\sim}{r}, t)$ and $S(\underset{\sim}{r}, t)$ satisfying canonical uncoupled wave equations with the respective velocities

$$\left(\frac{\lambda + 2\mu}{\rho}\right)^{1/2}, \quad \left(\frac{\mu}{\rho}\right)^{1/2} .$$

Many possibilities are suggested by the coupled equations for $P(\underset{\sim}{r}, t)$ and $S(\underset{\sim}{r}, t)$, apart from their use in the solution of (iv) above. They lead to a statement of conditions on the earth model under which P and SV waves can propagate independently (at any frequency). We also use them to obtain approximate reflection coefficients for upper mantle transition regions which generate observed precursors to the phase PKPPKP, finding that the extent of velocity gradient anomaly in such regions must be less than about 4 km, in order to observe short period (1 sec) reflections.

Our numerical study of core diffraction provides an explanation for the observed polarization towards SH of diffracted S waves, and also shows that there is a slight dispersion effect on $dT/d\Delta$ data, obtained for P in the range beyond 90°, which can and must be allowed for in accurate Herglotz-Wiechert inversion studies. The numerical methods developed for discussion of (iv) are expected to have wider applications in seismological studies of the earth's core, mantle, and crust.

<u>Body Wave Reflections from Velocity Gradient Anomalies,</u> by Paul G. Richards

The frequency-dependent reflection coefficient R (= reflected/incident displacement amplitudes) is calculated for several models of transition regions in the earth's mantle. To generate an observable short period precursor to P'P', we find that the effective thickness L of the transition zone must be smaller than has hitherto been generally supposed. Thus, for a smooth variation of elastic properties across the 630 km transition, we fine $R(2 \text{ sec}) > 0.025$ only if $L < 4$ km. R is also estimated for models with second-order velocity discontinuities, for which $R(1 \text{ sec}) > 0.025$ only if $L < 5$ km, even in the case of a 20% total change in velocity.

C. SEISMIC SOURCE THEORY AND OBSERVATIONAL STUDIES

Observation and Interpretation of Tectonic Strain Release Mechanisms, by Max Wyss (Ph.D. Thesis)

Surface displacements that followed the Parkfield, 1966, earthquakes were measured for two years with six small-scale geodetic networks straddling the fault trace. The logarithmic rate and the periodic nature of the creep displacement recorded on a strain meter made it possible to predict creep episodes on the San Andreas fault. Some individual earthquakes were related directly to surface displacement, while in general, slow creep and aftershock activity were found to occur independently. The Parkfield earthquake is interpreted as a buried dislocation.

The source parameters of earthquakes between magnitude 1 and 6 were studied using field observations, fault plane solutions, and surface wave and S-wave spectral analysis. The seismic moment, M_o, was found to be related to local magnitude, M_L, by $\log M_o = 1.7\,M_L + 15.1$. The source length vs. magnitude relation for the San Andreas system was found to be: $M_L = 1.9 \log L - 6.7$. The surface wave envelope parameter AR gives the moment according to $\log M_o = \log AR_{300} + 30.1$, and the stress drop, τ, was found to be related to the magnitude by $\tau = 0.54\,M - 2.58$. The relation between surface wave magnitude M_S and M_L is proposed to be $M_S = 1.7\,M_L - 4.1$. It is proposed to estimate the relative stress level (and possibly the strength) of a source-region by the amplitude ratio of high-frequency to low-frequency waves. An apparent stress map for southern California is presented.

Seismic triggering and seismic shaking are proposed as two closely related mechanisms of strain release which explain observations of the character of the P wave generated by the Alaskan earthquake of 1964, and distant fault slippage observed after the Borrego Mountain, California earthquake of 1968. The Alaska, 1964, earthquake is shown to be adequately described as a series of individual rupture events. The first of these events had a body wave magnitude of 6.6 and is considered to have initiated or triggered the whole sequence. The propagation velocity of the disturbance is estimated to be 3.5 km/sec. On the basis of circumstantial evidence it is proposed that the Borrego Mountain, 1968, earthquake caused release of tectonic strain along three active faults at distances of 45 to 75 km from the epicenter. It is suggested that this mechanism of strain release is best described as "seismic shaking."

The changes of apparent stress with depth are studied in the South American deep seismic zone. For shallow earthquakes the apparent stress is 20 bars on the average, the same as for earthquakes in the Aleutians and on oceanic ridges. At depths between 50 and 150 km the apparent stresses are relatively high, approximately 380 bars, and around 600 km depth they are again near 20 bars. The seismic efficiency is estimated to be 0.1. This suggests that the true stress is obtained by multiplying the apparent stress by ten. The variation of apparent stress with depth is explained in terms of the hypothesis of ocean floor consumption.

The Theory of Stress Wave Radiation from Explosion in Prestressed Media, by C. B. Archambeau

Stress wave radiation from underground explosions has been observed to contain an anomalous shear wave contribution which is most likely of tectonic origin. In this paper the theoretical radiation field to be expected from an explosion in a prestressed medium is given under the assumption that no secondary low symmetry faulting on a large scale occurs, and that the total tectonic component of the field is due to stress relaxation around the roughly spherical fracture zone created by the explosive shock wave. Evidence for the occurrence of this simple kind of tectonic source is considered and it is concluded that this model is appropriate in many, if not most, instances involving underground explosions. Expressions for the spectrum of the radiation field and its spatial radiation pattern are given in terms of multipole expansions for the components of the rotation potential and the dilatation potential. Several possible rupture formation models are treated. All models show that the tectonic radiation is of simple quadrapole form, as has been observed. The energy radiated due to stress relaxation is considered in detail and it is also shown that, in terms of the energy released, a dislocation source can be used as an equivalent for the stress relaxation effects.

The theoretical energy partition between compressional and shear waves for the tectonic field is in the ratio of (approximately) 1 to 10, so that the tectonic effects do not effect the direct compressional body wave particularly, but give rise to totally anomalous SH polarized waves (e.g., Love waves) and strongly effect Rayleigh-type surface waves, as is also observed. The theory can be applied to obtain estimates of source dimensions and the orientation and magnitude of the initial prestress field in the region of the explosion. In addition, application of this particular form of the general tectonic source theory to deep earthquakes and volcanic earthquakes, also appears to be reasonable in view of the probable high symmetry of the failure or phase transition regions for such events.

Seismic Radiation from Explosions in Prestressed Media and the Measurement of Tectonic Stress in the Earth, by C. B. Archambeau and Charles Sammis

Theoretical predictions of the radiation field from explosions in a prestressed medium may be made on the basis of a dynamical theory of stress relaxation in the vicinity of the shock-induced fracture zone created by an explosion In this case the field consists of the normal compressional wave field resulting from the conversion of the shock wave to an elastic wave plus an anomalous part due to the release of strain energy. In this study we consider the nature of the radiation field to be expected from such a source in an inhomogeneous earth, and determine the stress field required to explain the observations from a large underground explosion. The field is described in terms of radiation patterns as functions of frequency or alternately as the amplitude and phase spectrums at particular distances. These theoretical predictions are compared to the Love and Rayleigh wave radiation patterns and spectra from the nuclear explosion Bilby. Using the known source parameters, we obtain agreement between the observed radiation patterns and the predicted

patterns for a pure shear prestress field equivalent to a shear couple oriented approximately N10°W. Using the amplitude spectrum of the observed field adjusted for propagational effects, we find that the prestress was 70 ± 20 bars in the source area. We conclude that this approach can be utilized as a means of systematically measuring the stress field of the earth.

Seismicity of the San Gorgonio Pass, by Thomas C. Hanks and J. N. Brune

Twenty-three small events have been accurately located in the San Gorgonio Pass region of southern California by means of a seven-station portable array. All of these events are located north of the Banning fault, which is more seismically active than the Mission Creek fault farther north. The inference that thrust faulting predominates in this region is consistent with the pattern of seismicity and fault depths of up to 21 km. A single event ($M_L = 2.7$, $M_O = 1 \times 10^{19}$) has been considered in terms of Brune's predictions of the shear wave displacement spectrum. The energy computed from the displacement spectrum is two orders of magnitude lower than the Gutenberg estimate based on the M_L determination. This event has a stress drop of 3 bars.

Comparison of P-Wave Spectra of Underground Explosions and Earthquakes, by Max Wyss, Thomas C. Hanks, and Robert C. Liebermann

The P-wave displacement spectra of the underground explosions MILROW and LONGSHOT are compared to those of four shallow earthquakes of comparable body-wave magnitude (m_b) in the Aleutian Islands. The spectral data ($0.4 \leq T \leq 40$ sec) have been obtained from three vertical instruments at Pasadena, approximately 50° from the epicentral region common to the six events. A NOVAYA ZEMLYA explosion of comparable m_b was also analyzed. The peak spectral amplitude for the earthquakes occurs at periods approximately ten times larger than for equal m_b explosions, indicating that earthquakes have source dimensions roughly ten times larger than explosions. For $T < 1.5$ sec the spectra for both types of events are comparable, with respect to both absolute level and rate of decay (ω^{-2}) with increasing frequency. The explosion spectra peak sharply in the interval 2 sec $> T \geq 1$ sec and decay as ω for longer periods. The earthquake spectra, however, continue to increase to a long-period level. This spectral behavior at long periods suggests that for explosions an exponentially decaying pulse may be a better approximation for the source time function than a step. The greatest differences in spectral amplitudes occur at periods longer than 3 sec. The observed differences in the P-wave spectra provide a diagnostic method for discriminating between earthquakes and underground explosions.

<u>The Kuril Trench - Hokkaido Rise System: Large Shallow Earthquakes and Simple Models of Deformation,</u> by Thomas C. Hanks

Large shallow earthquakes of the Kuril Trench are distinct from those of the Aleutian and Peru-Chile Trenches in two important ways: 1) the rate of occurrence of events near or oceanward of the trench axis with tensional focal mechanisms is markedly lower than for the Aleutian Trench, and 2) the average apparent stress of fourteen events is almost an order of magnitude higher than for shallow events of either the Peru-Chile or Aleutian Trenches. An explanation of these observations is that the oceanic lithosphere forming the Kuril Trench - Hokkaido Rise system is acted upon by a horizontal compressive stress of several kilobars, in a direction normal to the Kuril Trench axis.

Calculations based on simple models of elastic deformation support this explanation. Unless the Kuril oceanic lithosphere has a strong nonelastic response on a time scale of a few million years, a horizontal compressive stress of at least several kilobars is necessary to maintain the Kuril Trench - Hokkaido Rise bathymetry. The oceanic lithosphere in this region has an effective (elastic) thickness of approximately 30 km and is capable of supporting deviatoric compressive stresses of several kilobars. The elastic thickness of the Kuril oceanic lithosphere agrees well with the thickness of the seismic zone beneath the Tonga arc.

<u>A Comparative Study of the Elastic Radiation Fields from Earthquakes and Underground Explosions,</u> by D. G. Lambert, E. A. Flinn, and C. B. Archambeau

A detailed analysis of the surface wave radiation from two underground explosions (the Bilby and Shoal events) and an earthquake (the Fallon event) with an epicenter at the site of one of the explosions indicates that:
1) The long period radiation from the earthquake is closely matched by a pure quadrapole source, but at higher frequencies the radiation patterns show asymmetries indicating rupture propagation effects and requiring additional higher order multipole terms for the source equivalent.
2) The radiation from the explosions corresponds closely to a superposed monopole and pure quadrapole source equivalent with no indication of higher order multipole terms contributing within a frequency band comparable to that investigated for the earthquake. These results are interpreted in terms of a stress relaxation source theory. The behavior of the earthquake radiation field is found to be consistent with the predictions of the theory. The same theory is used to explain the anomalous quadrapole radiation from the explosion under the supposition that the quadrapole radiation arises from stress relaxation around a shock-generated fracture zone. In both cases the equivalent quadrapole is determined. A comparative analysis of the earthquake-explosion pair having common epicenters and points of observation illustrates the basic differences in the long-period radiation from these two kinds of sources. These results provide us with a basis for distinguishing between earthquakes and explosions as well as the means of estimating source parameters, such as stress, which are of fundamental geophysical interest.

Theory of the Seismic Source, by C. B. Archambeau

A summary of seismic source representation theory can be most economically given in terms of the Green's function solution to the equations of motion for an elastic medium. In this paper, the equations of motion are reduced to wave equations containing source terms. Their integral solutions are seen to be composed of a sum of three integrals. In the context of seismic source theory, the first of the integrals can be used to represent applied forces or force equivalents of a tectonic source, the second for tractions applied at the boundaries of the medium and for dislocation equivalents of a seismic source, and the third for initial value or relaxation sources corresponding to the spontaneous release of stored potential energy. Either of the first two representation integrals can be used to obtain the radiated field from an explosion, while the third gives the field due to a tectonic or earthquake source. Both the body force and dislocation equivalents can be used to represent a tectonic source, but require an assumption of the source time function while the initial value solution inherently contains this information. Thus the latter solution can be used to predict the spectral and spatial properties of the field from various kinds of tectonic sources. Predictions of these properties of the field from a tectonic source are given using the initial value theory and lead, upon comparison with similar spectral and spatial properties of explosive sources, to criteria for the discrimination of earthquakes from explosions.

A Comparative Study of the Tectonic Effects Associated with Underground Explosions and Earthquakes, by C. B. Archambeau

Observational data suggest that tectonic stress release of some sort occurs in the near vicinity of most underground explosions. These observations are summarized and compared to predictions of theoretical models for tectonic release; with the conclusion that explosions in a prestressed environment yield a seismic radiation field which can be described, to first order, as a superposition of a monopole component due to the converted explosive shock wave itself, plus an (anomalous) quadrupole component due to stress relaxation in the vicinity of the shock-induced fracture zone. In general the field can be explained in terms of stress relaxation near a roughly spherical shatter zone, so that in most cases induced low-symmetry fracturing (faulting) does not appear to be involved. In a few, exceptional cases, induced faulting with associated stress relaxation may be involved as a source of seismic radiation. The properties of explosive source radiation fields are contrasted with the corresponding properties of an earthquake field. A number of differences in radiation patterns and spectral properties are discussed, and on this basis criteria for discrimination of the two kinds of events are investigated. On the basis of observed differences for comparable events, as well as predicted theoretical differences, it is concluded that a principle and basic difference between an earthquake and a comparable explosion producing a radiated seismic field of the same or nearly the same total energy is the shift of the peak in the seismic displacement spectrum for the earthquake to a relatively lower frequency compared to that for the explosion. This effect results in different

m_b versus m_s ratios for the two kinds of events and a different variation of the L/R (Love to Rayleigh) ratio as a function of frequency. A second basic difference is in the shape of the radiation patterns for the two kinds of events. These differences are associated with the difference in the characteristic source dimension of the sources and in the presence of the strong monopole component for the explosion. An approach to the systematic investigation of similar differences for exceptional cases, including very low magnitude events, and for cases involving explosions with a large tectonic component, is discussed.

D. INSTRUMENTAL DEVELOPMENTS AND AUTOMATED DATA ACQUISITION/PROCESSING SYSTEMS DEVELOPMENT

<u>A Mercury Pendulum Seismometer</u>, by William W. Gile

A long-period mercury pendulum seismometer has been developed at the Seismological Laboratory, California Institute of Technology. The devices are presently operational in several locations throughout the world. The instruments exhibit extremely good sensitivity, stability, and signal to noise ratios in the .03 - .001 Hz range. Seismic waves of 3×10^{-4} Hz and tilts of a few parts in 10^{-11} radians have been observed.

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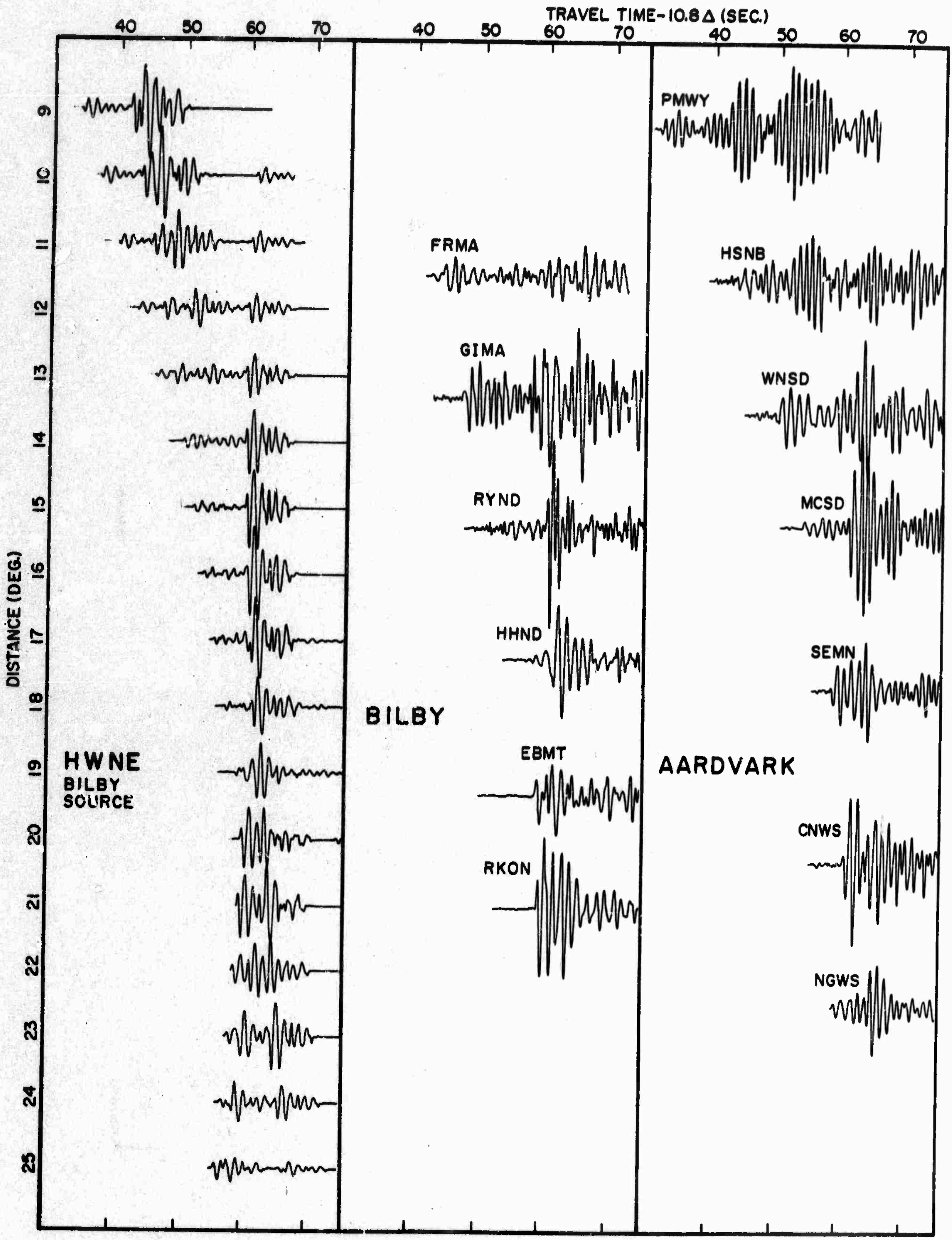
FIGURE CAPTIONS

Figure 1. Theoretical seismograms (HWNE) compared to observations from the Bilby and Aardvark events.

Figure 2. Automated data processing and analysis system.



TRAVEL TIME-10.8Δ (SEC.)
40
50
60
70
DISTANCE (DEG.)
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
HWNE
BILBY
SOURCE
BILBY
FRMA
GIMA
RYND
HHND
EBMT
RKON
AARDVARK
PMWY
HSNB
WNSD
MCSD
SEMN
CNWS
NGWS

Figure 1

AUTOMATED SYSTEM FOR TELEMETERED AND PORTABLE ARRAY DATA*

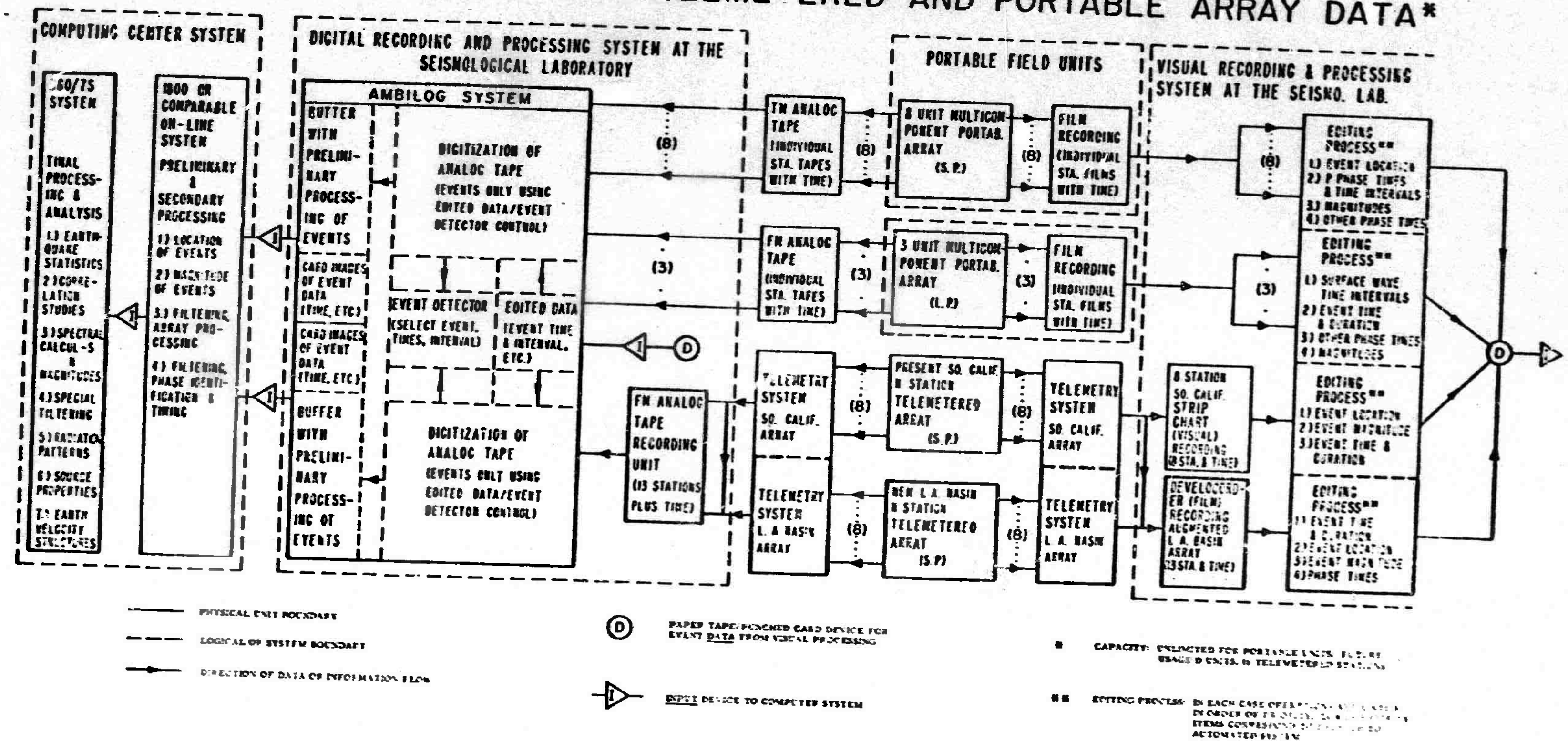


Figure 2

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